

METHOD, APPARATUS, AND ARTICLE FOR FORCE FEEDBACK BASED ON  
TENSION CONTROL AND TRACKING THROUGH CABLES

BACKGROUND OF THE INVENTION

Field of the Invention

5 The disclosure is generally related to haptic systems employing force feedback.

Description of the Related Art

Touch, or *haptic* interaction is a fundamental way in which people perceive and effect change in the world around them. Our very understanding of 10 the physics and geometry of the world begins by touching and physically interacting with objects in our environment. The human hand is a versatile organ that is able to press, grasp, squeeze or stroke objects; it can explore object properties such as surface texture, shape and softness; and it can manipulate tools such as a pen or wrench. Moreover, touch interaction differs fundamentally 15 from all other sensory modalities in that it is intrinsically bilateral. We exchange energy between the physical world and ourselves as we push on it and it pushes back. Our ability to paint, sculpt and play musical instruments, among other things depends on physically performing the task and learning from the interactions.

Haptics is a recent enhancement to virtual environments allowing 20 users to “touch” and feel the simulated objects with which they interact. Haptics is the science of touch. The word derives from the Greek *haptikos* meaning “being able to come into contact with”. The study of haptics emerged from advances in virtual reality. Virtual reality is a form of human-computer interaction (as opposed to keyboard, mouse and monitor) providing a virtual environment that one can 25 explore through direct interaction with our senses. To be able to interact with an environment, there must be feedback. For example, the user should be able to

touch a virtual object and feel a response from it. This type of feedback is called haptic feedback.

In human-computer interaction, haptic feedback refers both to *tactile* and *force* feedback. *Tactile*, or touch feedback is the term applied to sensations felt by the skin. Tactile feedback allows users to feel things such as the texture of virtual surfaces, temperature and vibration. *Force* feedback reproduces directional forces that can result from solid boundaries, the weight of grasped virtual objects, mechanical compliance of an object and inertia.

*Tactile* feedback, as a component of virtual reality simulations, was 10 pioneered at MIT. In 1990 Patrick used voice coils to provide vibrations at the fingertips of a user wearing a Dextrous Hand Master Exoskeleton. Minsky and her colleagues developed the "Sandpaper" tactile joystick that mapped image texels to vibrations (1990). Commercial tactile feedback interfaces followed, namely the "Touch Master" in 1993, the CyberTouch® glove in 1995, and more recently, the 15 "FEELit Mouse" in 1997.

Scientists have been conducting research on haptics for decades. Goertz at Argonne National Laboratories first used force feedback in a robotic tele-operation system for nuclear environments in 1954. Subsequently the group led by Brooks at the University of North Carolina at Chapel Hill adapted the same 20 electromechanical arm to provide force feedback during virtual molecular docking (1990). Burdea and colleagues at Rutgers University developed a light and portable force feedback glove called the "Rutgers Master" in 1992. Commercial force feedback devices have subsequently appeared, such as the PHANTOM™ arm in 1993, the Impulse Engine in 1995 and the CyberGrasp® glove in 1998.

25 Haptic devices (or haptic interfaces) are mechanical devices that mediate communication between the user and the computer. Haptic devices allow users to touch, feel and manipulate three-dimensional objects in virtual environments and tele-operated systems. Most common computer interface devices, such as basic mice and joysticks, are input-only devices, meaning that

they track a user's physical manipulations but provide no manual feedback. As a result, information flows in only one direction, from the peripheral to the computer. Haptic devices are input-output devices, meaning that they track a user's physical manipulations (input) and provide realistic touch sensations coordinated with on-screen events (output). Examples of haptic devices include consumer peripheral devices equipped with special motors and sensors (e.g., force feedback joysticks and steering wheels) and more sophisticated devices designed for industrial, medical or scientific applications (e.g., PHANTOM™ device).

Haptic interfaces are relatively sophisticated devices. As a user manipulates the end effector, grip or handle on a haptic device, encoder output is transmitted to an interface controller at very high rates. Here the information is processed to determine the position of the end effector. The position is then sent to the host computer running a supporting software application. If the supporting software determines that a reaction force is required, the host computer sends feedback forces to the device. Actuators (motors within the device) apply these forces based on mathematical models that simulate the desired sensations. For example, when simulating the feel of a rigid wall with a force feedback joystick, motors within the joystick apply forces that simulate the feel of encountering the wall. As the user moves the joystick to penetrate the wall, the motors apply a force that resists the penetration. The farther the user penetrates the wall, the harder the motors push back to force the joystick back to the wall surface. The end result is a sensation that feels like a physical encounter with an obstacle.

The human sensorial characteristics impose much faster refresh rates for haptic feedback than for visual feedback. Computer graphics has for many years contented itself with low scene refresh rates of 20 to 30 frames/sec. In contrast, tactile sensors in the skin respond best to vibrations that are more than an order-of-magnitude higher than visual rates. This order-of-magnitude difference between haptics and vision bandwidths often requires that the haptic interface incorporate a dedicated controller. Because it is computationally expensive to

convert encoder data to end effector position and translate motor torques into directional forces, a haptic device will often have its own dedicated processor. This removes computation costs associated with haptics and the host computer can dedicate its processing power to application requirements, such as rendering 5 high-level graphics.

General-purpose commercial haptic interfaces used today can be classified as either ground-based devices (force reflecting joysticks and linkage-based devices) or body-based devices (gloves, suits, exoskeletal devices). The most popular design on the market is a linkage-based system, which consists of a 10 robotic arm attached to a grip (usually a pen). A large variety of linkage based haptic devices have been patented (examples include US patent numbers 5,389,865; 5,576,727; 5,577,981; 5,587,937; 5,709,219; 5,828,813; 6,281,651; 6,413,229; 6,417,638). The arm tracks the position of the grip and is capable of exerting a force on the tip of this grip. To meet the haptic demands required to fool 15 one's sense of touch, sophisticated hardware and software are required to determine the proper joint angles and torques necessary to exert a single point of force on the tip of the pen. Not only is it difficult to control force output because of the update demand, the mass of a robotic arm introduces inertial forces that must be accounted for.

20 An alternative to a linkage-based device is one that is tension-based. Instead of applying force through links, cables are connected a point on a "grip" in order to exert a vector force on that grip. Encoders can be used to determine the lengths of the connecting cables, which in turn can be used to establish position of the cable connection point on the grip. Motors are used to create tension in the 25 cables, which results in an applied force at the grip. There is only one commercial tension based device available, through a Japanese company called Cyverse.

The SPIDAR-G is a 7 degree of freedom haptic device that allows translational, rotational and grip force. This design resulted from Dr. Seahak Kim's PhD work (Dr. Seahak Kim is currently an employee of Mimic Technologies, Inc.).

References for much of Dr. Seahak Kim's work on the SPIDAR-G have been listed above.

Predating Dr. Seahak Kim's work on the SPIDAR-G, Japanese Patent No. 2771010 and U.S. Patent No. 5,305,429 were filed that describe a "3D input device" as titled in the patent. This system consists of a support means, display means and control means. The support means is a cubic frame. Attached to the frame are 4 encoders and magnetic switches capable of preventing string movement over a set of pulleys. The pulleys connect the tip of each encoder to strings that are wound through the pulleys. Each string continues out of the pulley to connect with a weight that generates passive tension in the string. The ON/OFF magnetic switches allow the strings to be clamped in place on command from the host computer. The strings connect to the user's fingertip, which are connected to the weights through the pulleys. The user moves his or her fingertip to manipulate a virtual object in virtual environment, which is displayed through a monitor. As the user moves his or her fingertip, the length of the four strings change, and a computer calculates a three-dimensional position based on the number of pulses from the encoder, which indicate the change of string length between the pulleys and the user's finger. If the three-dimensional position of the fingertip is found to collide with a virtual object as determined by a controlling host computer, then the ON/OFF magnetic switch is signaled to grasp and hold each string so that movement is resisted. Forces are not rendered in a specific direction, but resistance in all directions indicates that a user has contacted a virtual object. When the fingertip is forced outside the boundary of a virtual object, the magnetic switch is turned off to release the strings. The user is then able to move his or her finger freely.

The "3 dimensional input device" introduced in US patent No. 5,305,429 is not capable of controlling or rendering directional forces. It is therefore not possible to render three-dimensional forces in the manner typically associated with a haptic device. In other words, this device is not capable of

simulating haptic effects such as the feel or contact with a virtual three-dimensional surface.

The “3 dimensional input device” cannot render controlled vector forces because of the following reasons, (i) it is impossible to display exact directional force, because the device can only grasp or release each string by ON/OFF magnetic switches and cannot impose an exact tension in each string; (ii) there is no accounting for the changing force applied by the weights attached to each string which provide a variable tension as the velocity of the moving weight changes the tension; (iii) there is no accounting for extraneous forces resulting from friction between the frame, pulleys, ON/OFF magnetic switches and the strings; and (iv) there is no initialization sequence described which is required for determining initial string lengths as need for determining string orientations and finger position so that forces can be reflected accurately. In summary this is not a true force feedback device, but instead is only a tracking mechanism with a single force effect (direction nonspecific drag). As an input device, the system also lacks a robust measurement method for determining the length of the strings, which results in substantial fingertip position measurement errors. There is also no means for measuring orientation of the finger (roll, pitch and yaw).

A system that combines virtual reality with exercise is described in US patent 5,577,981. This system uses sets of three cables with retracting pulleys and encoders to determine the position of points on a head mounted display. Using the lengths of the three cables, the position of the point in space is found. Tracking three points on the helmet (9 cables) allows head tracking of 6 degrees of freedom. Three cables attached to motor and encoders are also used to control the movement of a boom that rotates in one dimension through a vertical slit in a wall. The boom also has a servomotor at its end, about which the boom rotates. It is claimed that the force and direction of force applied by the boom can be controlled via the cables, servo motor and computer software, but no details are provided for how this is accomplished.

Applications have been filed for patents in Japan and the US to support the SPIDAR-G (as discussed earlier). This apparatus was titled “three-dimensional input apparatus” and was filed under patent No. 2001-282448 in Japan, and a US patent application has also been submitted: No. 20010038376.

5 This device also consists of a support means, display means and control means similar to that described in US patent No. 5,305,429. However, this device uses “at least seven strings” to accommodate “at least six degrees of freedom” (actually the patent application only explains 7 degrees of freedom with 8 strings, but a claim is made for 6 degrees of freedom with seven strings). The mentioned

10 support means includes a cubic frame, where a motor and encoder are attached to at least seven locations on the frame. The tip of each encoder is connected to a spool on a motor, and this spool winds the string. The encoder and motor are rotated simultaneously. The motors are meant to create tension in the strings in place of the weights used in the earlier patent. Instead of the string attaching to

15 the users finger, the strings attach to a sphere shaped grip.

This grip has a mechanical structure that consists of two poles that are rotated based on the grasp force between the thumb and other fingers of the user. Two strings are connected to each of the four extremities of the two poles. If the user moves the tool to manipulate a virtual object in a virtual environment, as

20 displayed through a monitor, each string length is changed, and the computer is used to calculate a three dimensional position (translation, rotation and grasp information) based on the number of pulses from the encoder, which is an indication of a change in string length. If contact is made with a virtual object, the controlling computer is used to calculate the tensions in the strings that are

25 necessary to render force and torque at the grip.

The system described in Japanese patent 2001-282448 can therefore actively display translation, rotation, and grasp force. As a result, the user is able to “touch” virtual objects through the display of force. However, the above-mentioned “3 Dimensional interface device” requires at least seven strings

to determine position and render force, even if rotation and grip forces are not being applied, and, while the design described above is adequate for displaying seven degrees of force feedback, there are severe limitations imposed if less than seven degrees of force feedback are required.

## 5 BRIEF SUMMARY OF THE INVENTION

In one aspect of the invention, an input/output haptic interface is provided, to input the position of a tool(s) held by the user to a computer by directly determining position and orientation of the tool in a three-dimensional space. Tracking may be accomplished over as many as six degrees of freedom.

10 In another aspect, a method is provided, for determining a tool position through cable lengths with minimal error. Position of the tool may also be established with alternative tracking mechanisms such as through infrared, electromagnetic, gyro or acceleration sensors.

15 In another aspect, an input/output haptic interface is provided, to render forces to a point on a tool held by a user over two or three dimensions as signaled from software running on a host computer. Multiple sets of cables render vector forces to multiple points on a tool. Alternatively, multiple sets of cables render vector forces to points on multiple tools used in the same workspace.

20 In yet another aspect, a new calibration system is provided, for maintaining tool position accuracy with minimal user intervention, even after powering down and reactivation of the apparatus over multiple iterations.

25 In a further aspect, an input/output haptic interface provides a user with the “touch” sensation generated as a result of interaction with virtual environments, which could include force effects such as contact force resulting from tool collision with rigid or deformable virtual surfaces, the pull, push, weight or vibration of a virtual object contacting a tool(s), and/or viscous resistance and inertia experienced as a tool moves through virtual fluid.

In still a further aspect, an interface relays position and forces data to and from a robot (or similar system). Control of the robot (or similar system) through the invention can be used to establish telepresence.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

5           In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example, the shapes of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the  
10 elements as drawn, are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

Figure 1 is a block diagram that describes the components of the invention and how they relate to each other.

15           Figure 2 is a perspective view of one possible configuration of the interface device which includes tool translation effector components, cables and a supporting frame.

Figure 3 is a perspective view of one possible configuration of a tool translation effector device.

20           Figure 4 is a perspective view of another possible configuration of a tool translation effector device that uses an eyelet rather than a pulley and associated parts.

Figure 5 is a top view of the tool translation effector device shown in Figure 3.

25           Figure 6 is a side view of the tool translation effector device shown in Figure 3.

Figure 7 shows the grooves on the second pulley of the tool translation effector device that help evenly guide a winding cable.

Figure 8 is a perspective view of another possible configuration of the interface device, which includes tool translation effector components, cables, a supporting frame, a port and a minimally invasive othoscope.

Figure 9 shows a typical cycle of information/action flow as position 5 of a tool is detected and force is displayed at the tool.

Figure 10 shows a generalized schematic for rendering force and tracking a tool over two dimensions.

Figure 11 shows a configuration of the invention that will allow forces to be applied and controlled on a port, or trocar, over two dimensions in a system 10 that might be used for minimally invasive surgery simulation. The system also allows for tracking the position of the point on the port where the cables connect.

#### DETAILED DESCRIPTION OF THE INVENTION

While the system described in Japanese patent 2001-282448, and outlined in the background section of this document, provides significant 15 advantages over the previous art, there are still some problems that remain unaddressed. For example, when calculating the length of each string, error is introduced because a changing spool diameter resulting from string wrapped over itself on the spool is not accounted for; the device calculates rotation based on the length change in eight strings, where a minor error in length variation of one string 20 can substantially affect accuracy (calculation algorithm is not robust about rotation); there is no initialization sequence provided, which is necessary for determining initial string length as required for determining position, orientation and grip, and minimizing associated error; the grip is connected with eight strings, so workspace is limited if the user wishes to avoid tangling the strings; and there is no 25 accounting for extraneous forces resulting from friction between the frame, pulleys, motors and strings.

In the following description, certain specific details are set forth in order to provide a thorough understanding of various embodiments of the

invention. However, one skilled in the art will understand that the invention may be practiced without these details. In other instances, well-known structures associated with motors, motor controllers, computers, microprocessors, memories and the like have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the embodiments of the invention.

5 Unless the context requires otherwise, throughout the specification and claims which follow, the word "comprise" and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is as "including, but not limited to."

10 The headings provided herein are for convenience only and do not interpret the scope or meaning of the claimed invention.

Figure 1 shows a tension based force feedback system 10 using cables, includes a number of devices or modules, such as: an interface module 100 to detect translational and rotational signals concerning the tracking of a tool manipulated by the user; a control module 200 to convert analog and pulse signals generated from the interface device 100 to digital signals and to relay force signals to the mentioned interface device 100; a calculation module 300 to control force feedback, to calculate the position of a tool based on translation and rotational manipulation by the user, and to mathematically represent objects and/or environments that might interact with the tool; a display module 400 for the user to perceive visual and/or audible information about the tool 160 and objects and/or environments which are modeled in the calculation device 300; and a robotic module 500, which in those embodiments of the invention that are so configured, receives control instructions from, and provides feedback signals to, the calculation module 300.

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Figure 2 shows one possible configuration of the interface device 100. This configuration of the interface device includes a frame 110, four cable control units, or tool translation effector devices 120, 130, 140, and 150, a tool 160, and a sensor array, or tool rotation detection device 170.

Reference to the tool 160 may also be construed to refer to a connection point to which the cables 11, 12, 13, and 14 are attached. According to some embodiments of the invention, a separate tool, device, handle, or other implement is coupled to the tool 160.

5 The frame 110 in Figure 2 represents one possible structure for supporting the tool translation effector devices 120, 130, 140, and 150 and the other components that are located within a three dimensional space. The frame 110 can be constructed from a variety of materials, such as sheet metal, trusses or rigid plastic, and can take the form of a wide variety of geometries that partially

10 enclose a three dimensional volume. The main requirement of the frame is to provide rigid support of elements such as the detection devices 120, 130, 140, and 150. At the same time the frame geometry should allow the user to freely manipulate the tool 160 within a prescribed workspace, without excessive collision of the tool 160, or the user's hands, with the frame 110. In the embodiment

15 illustrated in Figure 2, the prescribed workspace is approximately cubic with the volume partially enclosed by sides 111-119.

Each tool translation effector device 120, 130, 140 and 150 is positioned in three-dimensional space, and coupled at a corresponding anchor point to the frame 110. In the embodiment of Figure 2, the tool translation effector device 120 is positioned at the end of the upper right arm on the frame side 111, the tool translation effector device 130 is positioned at the end of the upper left arm on the frame side 112, the tool translation effector device 140 is positioned at the lower front of the frame in the center of side 115, and the tool translation effector device 150 is positioned at the lower back of the frame in the center of side 116.

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25 Tool translation effector devices 120 and 130 are centered in-between the tool translation effector devices 140 and 150 when viewed along the X-axis. Tool translation effector devices 140 and 150 are centered in-between the tool translation effector device 120 and 130 when viewed along the Y-axis. The tool translation effector devices 120, 130, 140 and 150 can be positioned in a variety of

configurations, and are not limited to that illustrated by Figure 2. The main objective when placing the tool translation effector devices 120, 130, 140 and 150 is to maximize the volume enclosed by the devices 120, 130, 140, 150 given the geometry of the frame 110.

5 Figure 3, 5 and 6 show detailed views of an illustrative one of the tool translation effector devices 120, 130, 140, 150. While translation effector device 120 is described for the purpose of illustration, it will be understood that, according to one embodiment of the invention, translation effector devices 130, 140, and 150 are substantially identical in structure and operation.

10 The illustrated tool translation effector 120 includes a mounting system 121, a pulley 122, a first bearing 123, a motor 124, an encoder 125, a spool 126, a cable 11, a second bearing 128, and a motor brake 129.

15 The four tool translation effector devices 120, 130, 140 and 150 of Figure 2 are oriented so that spools 126 generally guide the cables 11, 12, 13 and 14 toward the tool 160 with the objective of minimizing friction in the cable run (i.e., path) to the tool 160.

20 The mounting system 121 of each tool translation effector 120, 130, 140, 150 provides a path that guides the cable 11 from the spool 126 to the pulley 122, while providing stability for the spool 126 and the pulley 122, so that the center of the axis of each stays fixed in position when tension is applied to the cable 11. The mounting system 121 also provides a structure to couple the respective tool translation effector device 120, 130, 140, 150 to the frame 110. The mounting system 121 also positions the pulley 122 away from both the frame 110 and the spool 126 in a manner that enables ideal use of tool workspace. The 25 mounting system 121 may vary in size or geometry depending on workspace requirements.

The mounting system 121 includes a link 121a that is fixed to a bracket 121c. A rotary fulcrum 121b is attached to link 121a through a secondary bearing 128. The rotary fulcrum 121b can rotate about an axis that is

perpendicular to the adjacent face of link 121a. The secondary bearing between link 121a and rotary fulcrum 121b allows smooth rotation around an axis defined by hole 121e of Figure 5 as illustrated by arrow 121f (see Figure 6). The hole 121e runs through the center of the rotary fulcrum 121b, and the cable 11 passes

5 through the hole 121e. The cable 11 is guided to the pulley 122 from the spool 126 through the hole 121e. The pulley 122 is mounted to the rotary fulcrum through bracket 121d. The pulley 122 rotates around bearing 123 as illustrated by arrow 121g (Figure 6), which lies between bracket 121d and the pulley 122. In addition to its attachment to link 121a, bracket 121c is attached to the motor 124,

10 the brake 129, and also to the frame 110.

Each motor 124 is typically a DC motor that displays minimal back drive friction. The shaft of each motor 124 is drivingly coupled to a spool 126, which is in turn coupled to a cable 11. When the motor 124 turns the respective pulley 126, the cable 11 wraps or unwraps around the pulley 126. Tension occurs

15 in each cable 11, 12, 13 and 14 since the cables 11, 12, 13 and 14 pull at the tool 160 in opposing directions. The display tension to each cable 11, 12, 13 and 14 is based on the torque applied by the motors 124 to the spool 126 as governed by the control device 200. In order to reduce backlash, a gear is not used, however some embodiments may include a gear where suitable.

20 An encoder 125 is coupled to each motor 124 and converts the user's manipulation as represented by rotation of the motor shaft into electrical pulses that are sent to the control device 200. Typically, an optical encoder is used with a resolution of 1024 pulses per rotation of the motor shaft. However, a variety of optical encoders can be used that have a wide range of resolutions. An encoder is therefore chosen based on application requirements and price

25 constraints. Determining translational movement of the tool 160 can be calculated from the length of each cable 11, 12, 13 and 14, which is determined from encoder 124 pulse signals. There is a mathematical relationship between cable length change, diameter of the spool 126, and the pulses per rotation. The spool 126 can

be made of a variety of materials, such as aluminum, steel, rigid plastic or any other stiff material. The spool 126 may be grooved as shown in Figure 7, allowing the cable to wrap evenly about spool 126, although such is not required.

Figure 4 shows, according to an alternative embodiment, a cable 5 control unit 135, wherein the pulley 122, the first bearing 123, the second bearing 128, and parts 121a, 121b and 121d (shown in Figure 3) are omitted. In the place of these components is a low friction eyelet 122 that guides the cable 11 from the spool 126 through the mounting system 121. The cable control unit 135 has fewer moving parts than the cable control unit 120 described with reference to Figures 3, 10 5, and 6, but may, in some applications, introduce more drag to the associated cable 11.

The cables 11, 12, 13 and 14 connect between the spools 126 of the tool translation effecters to the tool 160. The cables 11, 12, 13 and 14 are ideally made of a material that is substantially inelastic under tension, such as Dacron 15 fishing line, but any string, wire or other cable that is flexible, durable and exhibits minimal stretch under tension can be used. The cables 11, 12, 13 and 14 connect to a point, or series of points in close proximity, on the tool 160 or tool holder. The tool 160 might be a stylus, pen, pliers, wrench, forceps, needle holder, scalpel, endoscope, arthroscope, minimally invasive surgical tool or other mechanical or 20 medical tool. The tool could be free floating as illustrated in Figure 2, or might move through a pivot point, such as the port 172 as illustrated in Figure 8, or the port 174 of Figure 11. Any object that can be connected to the cables 11, 12, 13 and 14, such that the cables 11, 12, 13 and 14 can apply vector forces to a point, or series of points in close proximity, on the object through cable tension, may be 25 considered the tool 160 as used herein. The cables 11, 12, 13, 14, apply a vector force to the tool 160.

According to an embodiment of the invention, the tool 160 also carries a sensor array 170 having one or more sensors, such as gyro sensors, acceleration sensors, infrared or electromagnetic sensors that can relay signals to

the control module 200. The purpose of these sensors is to relay information that can be used to determine tool orientation (roll, pitch and yaw) at the control module 200. Such sensors can also be used to relay information about the tool translation in the x, y and/or z directions in three dimensional space instead of, or in addition 5 to, the encoders 124 to determine the cable 11, 12, 13, and 14 lengths. Such sensors are commercially available from a wide variety of vendors and take a wide variety of shapes and configurations, so the details of these sensors have not been illustrated in the figures. The wires and/or wireless transmitters/receivers for transferring sensor signals from the sensor array 170 to the control module 200 10 are also not shown in the figures, although in at least one embodiment the cables 11, 12, 13, 14 may carry such signals.

As has been previously explained, according to some embodiments of the invention the tool 160 comprises a connection point to which the cables 11, 12, 13, and 14 are attached. A separate tool or device may then be coupled to the 15 tool 160. Accordingly, the sensor array 170 may be configured to detect rotation of the separate tool, as it moves or rotates in one or more axes within the tool 160.

According to another embodiment, the tool 160 includes a vibrating element attached, whose frequency and magnitude of vibration are regulated by the control module 200. The vibration element may be used to create tactile 20 effects. Vibration can also be used to simulate different materials. For example, a dissipating vibration signal at a high frequency might be used when simulating contact with steel as compared to a dissipating vibration signal at a lower frequency, which could be used when simulating contact with wood. Suitable vibrating elements are generally known, such as those employed in paging devices 25 and cellular phones, so will not be discussed in detail in the interest of brevity.

The control module 200 sends control signals to the motors 124 and receives signals from the encoders 125 of each tool translation effector device 120, 130, 140, 150. The control module 200 includes three primary components; a motor controller 210, which controls tension in each cable 11, 12, 13 and 14 via

the motors 124 as directed by the calculation module 300; an encoder counter 220 that receives and counts pulse signals from the encoders 125 and provides these counts to the calculation module 300; and an A/D converter 230 that converts analog signals transmitted from each tool translation effector device 120, 130, 140, 5 150 to digital signals that are relayed between the calculation module 300 and the control module 200.

The calculation module 300 consists of a local processor, memory storage and associated components on a printed circuit board for implementing local software control. The calculation module 300 may also include a remote 10 computer, such as a conventional Pentium processor type or workstation with conventional memory and storage means. The remote computer may transfer data to the local processor through connections such as USB, serial, parallel, Ethernet, Firewire, SCSI, or any other means of transferring data at a high rate. The calculation module 300 processes information via software control. The 15 functions of the calculation module 300 may be classified into five parts or functions: an object/environment representation function 310, a position calculation function 320, a collision detection function 330, a force control function 340, and an application recording function 350.

According to an embodiment of the invention, some or all of the 20 processing tasks, including those described with reference to the control device 200 and the calculation device 300, may be performed by a conventional system or workstation.

The object/environment representation function 310 manages and controls modeling information about virtual (or real) objects, the three dimensional 25 environment, the tool 160, and determines the proper interaction between the objects, environment and the tool 160. The object/environment representation function 310 might also include information about a robotic module 500, information sent from the robotic module 500, and/or how movement of the tool 160 effects navigation of the robotic module 500. The visual representation of

these objects is relayed from the object/environment representation function 310 to the display module 400. The position calculation function 320 determines the position of the tool 160 by processing signals from the control module 200 about translation and rotational movement of the tool 160. The collision detection 5 function 330 determines whether a collision has occurred between modeled objects and the tool 160. This might also include the indication of existing environmental effects such as viscous resistance and inertia experienced as a tool 160 moves through virtual fluid. When the system 10 is used to control a robot associated with the robotic module 500, collisions may be collected from the robot 10 as it collides with real objects. The force control function 340 is used to calculate tension of each cable 11 that is appropriate for rendering reaction forces that take place at the tool 160. The summation of vector forces in the cables 11, 12, 13 and 14 will equal the reaction force at the tool 160. Such forces might be the result of reaction forces collected by a robot as it interacts with real objects. The 15 application record function 350 manages all other software interaction that takes place in an application that utilizes the system 10.

The display module 400 displays manufactured virtual objects modeled through the calculation module 300. The display module 400 might also be used to convey visual information about real objects, such as in the case of 20 using the system 10 to control the robotic system 500 as it interacts with real objects. The display module 400 is typically understood to be a conventional video monitor type and may be, for example, NTSC, PAL, VGA, or SVGA. The display module may also consist of a head mounted display or a video projection system. The display module 400 may relay a 2D representation or a stereoscopic 25 representation for 3D projection. The display module 400 might be used, for example, to collocate stereoscopic representations into the workspace of the system 10. This could be accomplished by placing the face of a monitor between sides 116 and 117 or the images could be projected through mirrors located at the back, bottom or top of the frame 110. Stereoscopic images may also be relayed

through a head mounted display. The display module 400 may relay virtual environments where the entire environment can be classified as a rendered graphical image. The display module 400 may also transmit augmented environments where graphical rendering is overlaid onto video feeds or "see 5 through" displays of real environments. The display module 400 could also transmit pure video of real environments, such as might be the case when the system 10 is used to control a robot operating in a real environment.

In one embodiment the system 10 performs a variety of processes. A process to establish the initial length of each cable 11, 12, 13, and 14 is 10 achieved through processing transmitted signals between the calculation device 300 and each encoder counter device 220 and by utilizing a history of encoder pulse counts from each tool translation effector 120, 130, 140 and 150 as stored in the calculation device 300. The system 10 performs the process of relaying position and orientation (roll, pitch and yaw) information about the tool 160 to the 15 calculation device 300 through optical encoders and/or sensors such as gyro sensors, acceleration sensors, infrared or electromagnetic tracking mechanisms located in and/or around the tool 160. The system 10 performs the process of establishing the position and orientation (roll, pitch and yaw) of the tool 160 in three dimensional space at the calculation device 300. The system 10 performs 20 the process of determining the position and orientation of the tool 160 with the calculation device 300 from the signals sent by the control device 200 and/or the tool 160 to the calculation device 300.

The system 10 further performs the process of establishing in the calculation device 300 a force response that is appropriate at the tool 160 based 25 on position and orientation of the tool 160 as it relates to virtual or real objects defined at the calculation device 300. The system 10 carries out the process of determining tension values in each cable 11, 12, 13, and 14 that will deliver a force response to the tool 160 as determined at the calculation device 300, and controlling tension in each cable 11, 12, 13, and 14, by driving the motor 124 of

each tool translation effector devices 120, 130, 140, 150 based on the tension values determined in the calculation device 300. Finally, the system 10 performs the process of relaying visual and audible information to the display device 400 from the calculation device 300 about the location and orientation of the tool 160

5 and virtual or real objects that the tool 160 may be interacting with.

A typical cycle of information/action flow is shown in Figure 9, however, there would likely be more acts or steps in the case of representing a very complex environment. The steps of Figure 9 utilize the processes outlined above.

10 A process for establishing the initial length of each cable 11, 12, 13, and 14 is described below. According to one embodiment of the invention, these lengths are determined before the position of the tool 160 is calculated.

Calibrating these lengths can include the following acts:

15 1) The point on the tool 160 where the cable 11 is attached is moved to the pulley 122 of the tool translation effector 120 located on the upper right arm of the frame side on side 111. At this calibration point ( $P_1$ ), the length of cable 11 extending from the pulley 122 to the tool 160 is considered to be 0 cm. The counter value of the encoder 125 of the tool translation effector 120 is then set to 0 by the calculation device 300 while the tool 160 is in this position. The 20 encoder counts of each tool translation effector 120, 130, 140 and 150 are recorded at this position.

25 2) The point on the tool 160 where the cable 12 is attached is moved to the pulley 122 of the tool translation effector 130 located on the upper left arm of the frame on side 112. At this calibration point ( $P_2$ ), the length of cable 12 extending from the pulley 122 to the tool 160 is considered to be 0 cm. The counter value of the encoder 125 of the tool translation effector 130 is then set to 0 by the calculation device 300 while the tool 160 is in this position. The encoder counts of each tool translation effector 120, 130, 140 and 150 are recorded at this position.

3) The point on the tool 160 where the cable 13 is attached is moved to the pulley 122 of the tool translation effector 140 located on the lower front portion of the frame on side 115. At this calibration point ( $P_3$ ), the length of cable 13 extending from the pulley 122 to the tool 160 is considered to be 0 cm.

5 The counter value of the encoder 125 of the tool translation effector 140 is then set to 0 by the calculation device 300 while the tool 160 is in this position. The encoder counts of each tool translation effector 120, 130, 140 and 150 are recorded at this position.

4) The point on the tool 160 where the cable 14 is attached is moved to the pulley 122 of the tool translation effector 150 located on the lower back portion of the frame on side 116. At this calibration point ( $P_4$ ), the length of cable 14 extending from the pulley 122 to the tool 160 is considered to be 0 cm. The counter value of the encoder 125 of the tool translation effector 150 is then set to 0 by the calculation device 300 while the tool 160 is in this position. The encoder counts of each tool translation effector 120, 130, 140 and 150 are recorded at this position.

5) There is now a relationship between the number of encoder pulses and the change in distance between the tool 160 and the pulleys 122 attached to the tool translation effecters 120, 130, 140 and 150. The method for determining cable length and the position of the tool will be described later in this document. At this point, the recorded encoder counts are adjusted to account for the fact that some pulse counts were recorded before the counter value was set to zero. Values counted before the encoder was set to zero are offset by the appropriate amount. Steps 1 through 5 can be repeated to calibrate the device if it is believed that tracking inaccuracies exist, but normally, steps 1 though 5 are only required when powering up the system 10 for the first time with a new computer.

6) When powering down the system 10, the calculation device 300 first signals for the current to be removed from each spring actuated brake 128 attached to the motor spool 126 of the tool translation effecters 120, 130, 140 and 150. This prevents the motors 124 from spinning their respective spools 126. This

also keeps the encoders 125 locked in position. The calculation device 300 can then store the current pulse count from all the encoders 125 before completely powering down the system.

7) The next time the system 10 is powered up, the encoder pulse count values are then restored to each encoder 125 based on the values stored by the calculation device 300. Current to the brakes 128 is then re-established by the calculation device 300, which releases the hold on the motor spools 126. The tracking of the lengths of cables 11, 12, 13, and 14 can then resume as it did before the system 10 was last powered down.

10 The process to relay position, orientation and rotational information of the tool 160 to the calculation device 300 through optical encoders and/or sensors such as gyro sensors, acceleration sensors, infrared or electromagnetic tracking mechanisms located in and/or around the tool 160 will now be discussed. The optical encoders 125 of the tool translation effector devices 120, 130, 140, 150  
15 output analog signals that are transferred to an A/D converter 230. These signals are then converted to digital signals that are relayed to the calculation device 300 as encoder pulse counts. The digital signals are transferred to the position calculation part 320 of the calculation device 300 by way of the encoder counter part 220. The encoder pulse counts are used to determine the lengths of the  
20 cables 11, 12, 13 and 14.

The system 10 may employ a sensor array 170 having, for example, three gyro sensors or acceleration sensors to detect rotational movement of the tool 160. The sensor array 170 outputs analog signals depending on rotational acceleration or rotational degree of movement of the tool 160. The analog signals reflect rotation over three degrees of freedom (roll, pitch and yaw). These signals are transferred to A/D converter 230, which converts the signals to digital signals. The digital signals are then transferred to the position calculation part 320 of the calculation device 300 by way of the encoder counter part 220. The orientation (roll, pitch and yaw) of the tool 160 is determined based on the digital information

received according to means specified by the manufacturer of the gyro sensors or acceleration sensors. Such sensors can also be used to transfer translation information about the tool 160 in a similar manner to that described above. Other sensors such as infrared or electromagnetic tracking mechanisms could likewise

5 be used.

The process for finding tool position and orientation based on the digital information sent from the control device 200 to the calculation device 300 can be accomplished by a variety of means. In particular, there are various approaches to finding the tool position based on cable length. Some of these

10 options are discussed in the following.

One simple approach for finding the position of the tool 160 is based on solving four equations that define cable length. These equations contain only three unknown variables, which are the tool's rectangular coordinates,  $x$ ,  $y$ , and  $z$ . Equations 1 through 4 define the length  $l_n$  of each cable 11, 12, 13, 14 (where

15  $n=11, 12, 13, 14$ ), where  $x_i$ ,  $y_i$  and  $z_i$  define the positions of the calibration points  $P_i$  (where  $i=1,2,3,4$ ) and  $x$ ,  $y$  and  $z$  is the point where the cable 11, 12, 13 and 14 attach to the tool 160.

$$l_{11} = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} \quad (\text{Eq. 1})$$

$$l_{12} = \sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} \quad (\text{Eq. 2})$$

20

$$l_{13} = \sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} \quad (\text{Eq. 3})$$

$$l_{14} = \sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} \quad (\text{Eq. 4})$$

Consider the origin of the coordinate system to be in the center of the frame 110 shown in Figure 2. Consider sides 115, 116 and 117 to be of length  $2a$ . Consider sides 111 and 112 to be of length  $b$  and sides 113 and 114 to be  $2b$ .

25 Also consider sides 118 and 119 to be of length  $2c$ .

Equations 1 through 4 can be combined to determine a solution for the tool position (as defined by coordinates  $x$ ,  $y$  and  $z$ ) in terms of the lengths  $a$ ,  $b$  and  $c$ .

$$x = \frac{l_{12}^2 - l_{11}^2}{4a} \quad (\text{Eq. 5})$$

$$5 \quad y = \frac{l_{14}^2 - l_{13}^2}{4b} \quad (\text{Eq. 6})$$

$$z = \frac{l_{14}^2 + l_{13}^2 - l_{12}^2 - l_{11}^2 + 2a^2 - 2b^2}{8c} \quad (\text{Eq. 7})$$

Equation 5 can be found by squaring both sides of equations 1 and 2, subtracting equation 1 from equation 2, and then by isolating the variable  $x$ . Equation 6 can be found by squaring both sides of equations 3 and 4, subtracting equation 3 from equation 4, and then by isolating the variable  $y$ . Equation 7 can be found by squaring both sides of equations 1-4, adding equations 3 and 4 and from this subtract equations 1 and 2, and then by isolating the variable  $z$ . It should be noted that only three of equations 1-4 are necessary to solve for  $x$ ,  $y$ , and  $z$ , but using all four equations is a simpler approach. There are a variety of algebraic mathematical methods for solving for  $x$ ,  $y$  and  $z$  given equations 1, 2, 3 and 4 and the invention is not limited to the solving method described above.

To briefly summarize another method for determining the lengths of cable 11, 12, 13 and 14, the calibrations points  $P_1$ ,  $P_2$ ,  $P_3$ ,  $P_4$  discussed earlier form a tetrahedral volume,  $V$ . The position of the tool 160 where the cables 11, 12, 13 and 14 are attached can be used to divide this tetrahedron volume into four smaller tetrahedrons. If  $P$  is the cable connection point to the tool 160, consider  $V_1$  the volume formed by  $P$ ,  $P_2$ ,  $P_3$  and  $P_4$ ,  $V_2$  the volume formed by  $P$ ,  $P_1$ ,  $P_3$  and  $P_4$ ,  $V_3$  the volume formed by  $P$ ,  $P_1$ ,  $P_2$  and  $P_4$ , and  $V_4$  the volume formed by  $P$ ,  $P_1$ ,  $P_2$  and  $P_3$ . Since we know the side lengths of all of these tetrahedrons, we can determine these volumes from the side lengths (for example using Piero della Francesca's formula or Heron's formula) where the distance between the

calibration points and the tool 160 (in other words, the cable lengths) form the sides. It is then possible to use volume coordinates and shape functions to find the tool position (Zienkiewicz) as shown below.

$$x = \frac{V_1}{V} x_1 + \frac{V_2}{V} x_2 + \frac{V_3}{V} x_3 + \frac{V_4}{V} x_4 \quad (\text{Eq. 8})$$

5  $y = \frac{V_1}{V} y_1 + \frac{V_2}{V} y_2 + \frac{V_3}{V} y_3 + \frac{V_4}{V} y_4 \quad (\text{Eq. 9})$

$$z = \frac{V_1}{V} z_1 + \frac{V_2}{V} z_2 + \frac{V_3}{V} z_3 + \frac{V_4}{V} z_4 \quad (\text{Eq. 10})$$

The cable lengths described in equations 1-7 are determined through the number of encoder pulses that result from spinning the spool 126 of the tool translation effector devices 120, 130, 140, 150. Assume an encoder count of  $c$  pulses, where  $C$  represents the number counts per one complete motor shaft revolution (also known as encoder resolution). Also assume the spool 126 has a radius of  $r$  and that the groove separation 126a is  $d$ . The calibration process described earlier insures that the pulse count is zero when the cable length is zero. The pulse number increases as the cable unwraps from spool 126 of a tool 15 translation effector 120. Therefore, the length of each cable can be determined from the number of pulses based on equation 11, where the subscript  $i$  refers to the different tool translation effector devices 120, 130, 140, 150 and their associated cables 11, 12, 13 and 14.

$$l_i = \frac{c_i}{C} \sqrt{(2\pi r)^2 + d^2} \quad (\text{Eq. 11})$$

20 The difficulty with relying completely on equation 11 is that it is possible for a cable 11 to become miss wrapped so that it does not perfectly follow the grooves 126a of the spool 126. The cable 11 might also end up wrapping on top of previously wrapped cable if the spool 126 width and/or radius are not great enough. This can change variables  $r$  and  $d$  of equation 11, which will introduce

error if not accounted for. To address this source of error, the method described below can be employed.

$$L_{ij} = m_{ij} p_{ij} + n_{ij} \quad (\text{Eq. 12})$$

Equation 12 relates cable length at the calibration positions  $P_1$ ,  $P_2$ ,  $P_3$  and  $P_4$  to the recorded encoder pulses obtained during the calibration process. The cable length,  $L_{ij}$  is known at every calibration position  $P_j$ , where  $i$  refers to each of the four cables and  $j$  refers to the different calibration positions (where  $i=1..4$ ,  $j=1..4$  and  $i \neq j$ ). The number of encoder counts recorded at these lengths for the cables,  $p_{ij}$ , was recorded during the calibration process for calibration positions  $P_1$ ,  $P_2$ ,  $P_3$  and  $P_4$ . Given the known lengths,  $L_{ij}$ , of the cables at each calibration position and recorded pulse counts,  $p_{ij}$ , the linear curve of equation 12 can be fit to the data and variables  $m_{ij}$  and  $n_{ij}$  can be solved. Methods, such as the least mean squared method, could be used to fit this curve.  $n_{ij}$  will be close to zero so long as the encoder counters are set to zero at the calibration positions and the relationship between pulse count and length is truly linear. Otherwise, a spline or non-linear curve fit might be more appropriate for defining the relationship between cable length and pulse count

The process defined above for finding a linear relationship between encoder counts and cable length could be adapted to include more (or less) calibration positions as described for the calibration process. The user simply moves the point on the tool 160 where the cables 11, 12, 13 and 14 are attached to a specified calibration point. So long as the lengths of all the cables 11, 12, 13 and 14 are known at this point and the encoder counts are recorded at this position, then this data can be used to find a curve fit. The more calibration points the more accurate the curve fit will be.

It is also possible to use cable lengths as determined from alternative tool tracking mechanisms, such as infrared, electromagnetic, gyro or acceleration sensors. These sensors may or may not be fast enough to record tool positions at

haptic compatible rates. If such a tracking mechanism is considered accurate, but provides too slow of an update for haptics, the tracking mechanisms might be used to continuously calibrate a tracking system based on the encoders 126 of the tool translation effector devices 120, 130, 140, 150. The alternative tool tracking mechanisms would yield tool positions, which in turn can be used to determine cable lengths. These lengths can be associated with encoder counter values. A sample of such data can be used to fit a curve, such as that defined by equations 12, to find an updated relationship between cable length and encoder pulses at any given time. This method would therefore not require the user to move to any specific calibration positions. Note that  $n_{ij}$  of equation 12 does not have to be zero in this case, if the encoder counters are not set to zero at the calibration positions.

The process to establish in the calculation device 300 a force response that is appropriate at the tool 160 is normally determined according to the software application utilizing the system 10 under discussion. Typically, an application uses the tool 160 position and orientation information to determine if a collision has occurred with virtual objects. The force response can be rendered to simulate a wide range of effects. For example, a force response might simulate a collision of the tool 160 with a rigid or deformable virtual surface, the pull, push, weight or vibration of a virtual object contacting the tool 160, and/or viscous resistance and inertia experienced as a tool 160 moves through virtual fluid. Forces could also be derived from a robot touching real objects where the robot measures the reaction forces upon collision. The only limitation is that the force response determined at the calculation device 300 must be representable as a single vector force in the x, y and z direction at the point(s) where the cables 11, 12, 13, 14 connect with the tool 160. It is this vector force that the user will feel at the tool 160. This vector force can be updated at a rate that is appropriate for the application.

The process for determining tension values in each cable 11, 12, 13, and 14 that will deliver a force vector response to the tool 160 as determined by

the calculation device 300 will now be discussed. The force control part 340 calculates tension using the following equation.

$$J = (A\tau - f) + \alpha[\tau]^2$$

for

$$\min[J]^2 \Rightarrow 0$$

In equation 13,  $\tau$  is the tension where  $\tau = [\tau_1, \tau_2, \tau_3, \tau_4]$  in the cables

5 11, 12, 13 and 14,  $\alpha$  is a coefficient that displays stability of force,  $J$  is the target function. Consider  $w_i (i = 11, 12, 13, 14) (R^{3x1})$  a set of unit force vectors (in 3D) that are displayed along the direction of tension for each cable 11, 12, 13 and 14.

$A = \{w_{11}, w_{12}, w_{13}, w_{14}\} (R^{3x4})$  is a force matrix filled with the unit vector forces.

10  $f = (f_x, f_y, f_z)$  is the force vector that is to be displayed at the tool 160. The force control 340 calculates positive tension values, which minimizes the target function,  $J$  (in other words,  $J$  should end up close to zero). A good value to use for  $\alpha$  is 0.1, but the teachings herein are not limited to the use of this value. A variety of standard mathematical methods can be used to minimize the target function  $J$  and thus determine  $\tau$ .

15 The process to control tension in each cable 11, 12, 13, and 14 is accomplished by driving each motor 124, 134, 144 and 154 based on tension values determined in the calculation device 300. The force control part 340 of the control device 300 regulates motor torque by controlling the current sent to the motors 124. Each motor 124 applies torque to the attached spool 126. The torque 20 that accomplishes the appropriate tension in each cable 11 is dependent on the radius of the spool 126, which is accounted for by the force control part 340 of the control device 300.

A wide variety of structures can be used to control the process that relays visual and audible information to the display device 400 from the calculation 25 device 300. Typically, the location and orientation of the tool 160 and virtual or real objects that the tool 160 may be interacting with are displayed graphically. This allows the user to see how he or she is effecting a virtual environment or a

robot as the user moves the tool 160. This information is displayed according to the software application utilizing the system 10 under discussion and could constitute a vast range of possible formats. Audio output can also be utilized to display information resulting from tool 160 interaction with virtual objects or real

5 objects encountered through a robot.

There are a variety of configurations that the system 10 can employ that rely on the same concepts outlined above. According to one embodiment of the invention, The system 10 includes a tool shaft 180 that passes through a port 172, and is coupled at one end to the tool or attachment point 160. The cables 11, 10 12, 13 and 14 are attached to the point 160, which is coupled to the tool shaft 180, which in turn passes through the port 172 of interface device 20, as shown in Figure 8. While the system 10 applies translation forces in the x, y and z direction through cable 11 tensions to the point 160, or a set of points 160 in close proximity, on the tool shaft 180, the user will feel an insertion force (along with 15 pitch and yaw). In Figure 8, the insertion force is along the direction of the tool shaft 180 as confined by the port 172. Pitch and yaw are felt at the tool shaft handle with the pivot point at the port 172. Such a configuration is ideal to apply three degrees of freedom force feedback to minimally invasive instruments used when simulating a surgical procedure.

20 More degrees of force feedback, such as rotation around the tool shaft 180 and grip force at a handle of the tool shaft, can be added through additional motors independent of the cable system. For example, a motor in the tool shaft 180, or attached to the port 172, allows twisting force feedback, and a motor in the handle of the tool shaft 180 adds a squeezing grip force. Such uses 25 of motors to apply simple force feedback over 1 degree of freedom may be used to augment the system 10.

It is common when working through a port 172 to define forces in terms of moment around the port rather than vector forces as applied to the end of the tool attachment point 160. In this case, equation 15 should be adjusted to

accommodate moment about the port 172 which can be defined as  $M_x$  and  $M_y$ , and an insertion force  $f_i$  which is a vector force in the direction of the shaft of the tool 180.

$$J = (TA\tau - M) + \alpha[\tau]^2$$

for

$$\min[J]^2 \Rightarrow 0 \quad (\text{Eq. 14})$$

and

$$T = \begin{bmatrix} 0 & L_z & L_y \\ L_z & 0 & L_x \\ v_x & v_y & v_z \end{bmatrix}$$

5 In equation 14, consider the port 172 to be located at coordinate ( $N_x$ ,  $N_y$ ,  $N_z$ ) and  $L_x=x-N_x$ ,  $L_y=y-N_y$  and  $L_z=z-N_z$  where  $x$ ,  $y$  and  $z$  can be found using equations 5, 6 and 7.  $v=\{v_x, v_y, v_z\}$  is a unit vector that points from the port 172 axis origin (or the port pivot point) toward the point on the tool 160 where the cables 11, 12, 13, 14 are connected.  $M=\{M_x, M_y, f_i\}$  are the moment and insertion 10 force values prescribed by the user.

Embodiments of the invention are not limited to three degrees of force feedback freedom. In general,  $n$  degrees of force feedback can be accomplished with  $n+1$  cables or feedback devices. Figure 10 shows the schematic of a simple two-degree of freedom force feedback system 30, according 15 to another embodiment of the invention. The system 30 requires three cables 11, 12, 13 and three tool translation effector devices 120, 130 and 140. Equations 1, 2 and 3 define the length of the three cables 11, 12 and 13. Assume that tool translation effector device 120 lies at coordinate  $(0, b, 0)$ , tool translation effector device 130 lies at coordinate  $(-a, -b, 0)$  and tool translation effector device 140 lies 20 at coordinate  $(a, -b, 0)$ . Equations 1, 2 and 3 can be combined to isolate the  $x$  and  $y$  position values of the tool 160.

$$x = \frac{l_{12}^2 - l_{13}^2}{4a} \quad (\text{Eq. 17})$$

$$y = \frac{l_{12}^2 + l_{13}^2}{8b} - \frac{l_{11}^2 + a^2}{4b} \quad (\text{Eq. 18})$$

Equation 13 can be used, with two dimensional coefficient representations, to find two degrees of freedom force feedback in the  $x$  and  $y$  direction for the configuration shown in Figure 10.  $\tau$  is the tension where

5  $\tau = [\tau_{11}, \tau_{12}, \tau_{13}]$  in the cables 11, 12 and 13. Consider  $w_i (i = 11, 12, 13) (R^{e2x1})$  a set of unit force vectors (in 2D) that are displayed along the direction of tension in each cable 11, 12 and 13 in the  $x$ - $y$  plane.  $A = \{w_{11}, w_{12}, w_{13}\} (R^{e2x3})$  is a force matrix filled with the unit vector forces that correspond to the cables 11, 12 and 13.

10  $f = (f_x, f_y)$  is the 2D force vector that is to be displayed at the tool 160. It should be noted that a force along the  $z$  axis will be present if the tool 160 is moved outside of the  $x$ - $y$  plane. This force will always pull the tool 160 back toward the  $x$ - $y$  plane.

Figure 11 shows an interface device 40, according to another embodiment of the invention. The port 174 is elongated, with an upper end fixed

15 to a pivot point 171, while the point defined in other embodiments as the tool or attachment point 160 is defined in this embodiment as the lower end 165 of the port 174, which is free to move, within the constraints imposed by the device 40. In this configuration, the cables are attached to the lower end 165 of the port 174 rather than the tool 160. The port 174 rotates freely around the port axis origin 171

20 (or port pivot point) while the tool 190 itself slides freely through the port 174.

When finding the cable tensions that will result in moment about the port 174, which can be defined as  $M_x$  and  $M_y$ , a reduced version of equation 14 can be used. This is because insertion of the tool 190 is not being constrained, so the insertion force is essentially zero.  $T$  and  $M$  of equation 14 are simply redefined

25 to reflect the two degrees of force feedback problem, as shown below:

$$T = \begin{bmatrix} 0 & L_z & L_y \\ L_z & 0 & L_x \end{bmatrix} \quad \text{and} \quad M = \{M_x, M_y\}$$

In equation 14,  $\tau$  is the tension where  $\tau = [\tau_1, \tau_2, \tau_3]$  in the cables 11, 12 and 13, respectively. Consider  $w_i (i = 11, 12, 13) (R^{3x1})$  a set of unit force vectors (in 3D) that are displayed along the direction of tension in each cable 11, 12 and 13.  $A = \{w_{11}, w_{12}, w_{13}\} (R^{3x3})$  is a force matrix filled with the unit vector forces that 5 correspond to the cables 11, 12 and 13.

It may be seen that when the port 174 is rotated on the pivot point 171, the cable connection point 165 of the port 174 moves out of the x-y plane, as shown in dotted lines in Figure 11. Because  $f_z$  does exist when the point 165 is moved out of the x-y plane, it is not straight forward to convert from moments 10 about a port 174 to cable tensions using equation 16. By accounting for the forces that result in the z direction as the cable connection point 165 on the port 174 moves out of the x-y plane when the port 174 is rotated, accurate moments ( $M=\{M_x, M_y\}$ ), can be achieved.

While the x, y and z position on the port 174, where the cables 11, 15 12, 13 attach, can be solved using only equations 1, 2 and 3, it is also convenient to consider the constant length of the port shaft 15 as  $l_{14}$ . Under this assumption, equations 5, 6 and 7 can be used to determine position. This is only one example of how to determine position for the configuration of Figure 11. Methods similar to those discussed earlier also apply.

20 Rotational feedback and gripping force feedback may also be provided for the tool 190 of Figure 10, as has been described in more detail with reference to the tool shaft 180 of Figure 8.

Although not shown in any figure, a set of cables may be applied to multiple points on a tool so that different vector forces can be rendered at each 25 point. A single calculation device can be used to control all the cable sets, or different calculation devices, for example on separate circuit boards, may be used. The effect of applying separate force vectors to different points on a single tool yields the effect of rotational forces as felt by the user, or may serve to control the

movement of a jointed tool. Multiple sets of cables can also be used to apply force vectors to multiple tools that exist in the same workspace.

Although specific embodiments of and examples for the haptic system and method are described herein for illustrative purposes, various equivalent modifications can be made without departing from the spirit and scope of the invention, as will be recognized by those skilled in the relevant art. The teachings provided herein of the invention can be applied to other haptic systems, not necessarily the exemplary haptic system 10 generally described above.

The various embodiments described above can be combined to provide further embodiments. All of the above U.S. patents, patent applications and publications referred to in this specification are incorporated by reference. Aspects of the invention can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments of the invention.

These and other changes can be made to the invention in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims, but should be construed to include all haptic systems that operate in accordance with the claims. Accordingly, the invention is not limited by the disclosure, but instead its scope is to be determined entirely by the following claims.

All of the above U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet, including but not limited to US5305429; Seahak Kim, Masahiro Ishii, Yasuharu Koike, Makoto Sato, "Development of Tension Based Haptic Interface with 7 DOF :SPIDAR-G," ICAT2000, 25-27, Oct., 2000, National Taiwan University, Taiwan; Seahak Kim, Masahiro Ishii, Yasuharu Koike, Makoto Sato, "Design of a Tension Based Haptic Interface with 6 DOF," 4th World

Multiconference on Systemics, Cybernetics and Informatics (SCI2000) and the 6th International Conference on Information Systems Analysis and Synthesis (ISAS2000), Orlando, USA, in July 23-26, 2000; Seahak Kim, Masahiro Ishii, Yasuharu Koike, Makoto Sato, "Development of SPIDAR-G and Possibility of its Application to Virtual Reality," VRST2000, 22-25, Oct., 2000, Seoul, Korea; Seahak Kim, Masahiro Ishii, Yasuharu Koike, Makoto Sato, "Design of tension based haptic interface: SPIDAR-G," IMECE2000 (joint with ASME2000), 5-10, Nov., 2000, Orlando, USA; Seahak Kim, Masahiro Ishii, Yasuharu Koike, Makoto Sato, "Cutting edge Haptic interface device: SPIDAR-G," Proceedings of the 32nd ISR (International Symposium on Robotics), 19-21, April, 2001, Seoul, Korea; Seahak Kim, Shoichi Hasegawa, Yasuharu Koike, Makoto Sato, "Tension Based 7 DOFs Force Feedback Device: SPIDAR-G" by the IEEE Computer Society Press in the proceedings of the IEEE Virtual Reality Conference 2002, 24-28 March 2002 in Orlando, Florida; Seahak Kim, Shoichi Hasegawa, Yasuharu Koike, Makoto Sato, "Tension based 7 DOF Force Feedback Device," Trans. On ICASE, Vol. 4, No. 1, pp. 8-16, 2002; Seahak Kim, Jeffrey J. Berkley, and Makoto Sato, "A Novel Seven Degree of Freedom Haptic Device for Engineering Design," Journal of virtual reality, Springer UK (accepted), are incorporated herein by reference, in their entirety.

20 From the foregoing it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the invention. Accordingly, the invention is not limited except as by the appended claims.